

Paper No. 30

PHOTOGRAPHIC MEASUREMENT OF PARTICULATE SURFACE CONTAMINATION

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ABSTRACT

The particulate surface cleanliness of spacecraft is important to the proper functioning of certain spacecraft devices. This report reviews the limitations of some surface contamination measurements currently used, and shows how an approach based on the use of macrophotography has some inherent advantages over the usual methods for field measurement of assembled spacecraft. These advantages are that no contact with sensitive surfaces is required, the measurement is direct, and a permanent record is provided. The results of an experiment which compares particle visibility and sizing using 4X macrophotography with 37X photomicrography are provided. These results, based on the use of available equipment, indicated that macrophotography with non-optimized equipment provided reasonable accuracy down to 16 microns and that further refinement might allow the measurement of smaller particle sizes.

INTRODUCTION

Increasingly rigorous requirements for the control of particulate contamination of orbiting scientific payloads have made the study of spacecraft particulate surface contamination on the ground an important part of several programs. This is based on the consideration that many of these spacecraft contain devices which are sensitive to particles in their field of view and on their surface. The methods currently used to measure surface particulate contamination are generally not suitable for in situ examination of most assembled spacecraft since they require intimate contact of fluids or equipment with sensitive surfaces and are generally indirect. Therefore, the use of photographic measurement techniques which require no intimate contact, are direct, and provide a permanent record, were evaluated.

BACKGROUND

The reasons for concern about particulate contamination and current methods used to measure surface cleanliness were

explored with the following results.

Particulate Contamination Problems

As an example, based on Ref. 1, the star Canopus was used as a roll reference by the Surveyor, Lunar Orbiter and Mariner spacecraft. A consistent problem that plagued some of the spacecraft, particularly the 1964 Mariner, was that roll signal transients occurred frequently, occasionally causing loss of Canopus lock. Analysis and tests of possible mechanisms that could cause this behavior led to the conclusion that small dust particles were being released from the spacecraft by some means and were drifting through the star sensor field of view. Sunlight scattered from the particles then appeared as illumination equivalent to that from a bright star causing a roll error transient while the sensor was locked on Canopus. It was theorized that a 25-micron translucent dust particle with a diffuse scattering coefficient of 0.4 would appear as bright as Canopus at a distance of 66 cm from the star sensors. Large numbers of dust particles of this size and larger are collected on exposed surfaces even in the controlled environment of the spacecraft assembly area. It was considered plausible that minor vibrations or shock events could release particles from the spacecraft surface.

For spacecraft where the mapping of the celestial sphere and other items are of interest, the effect of dust particles is not a loss of lock-on as with the Mariner spacecraft. However, particulates in the field of view can appear as false targets that will degrade accuracy of the data returned. Cleanliness requirements called out in specifications are becoming more stringent. Several earlier programs stipulated requirements simply as "no visible particles," and recently the trend is toward the imposition of quantitative cleanliness standards with attempts to impose levels as low as MIL-STD-1246 Class 10. The various classes of standards are shown in Figure 1.

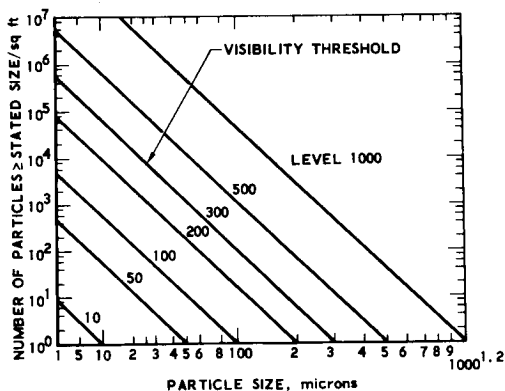


Fig. 1. Surface cleanliness standard

Particulate Contamination Measurement Methods

A literature survey was conducted to determine the applicability of current methods of measuring surface cleanliness of assembled spacecraft to this stringent accuracy.

Indirect Measurements. One of the most popular types of surface particulate measurements²⁻⁷ is conducted by flushing portions of the surface with a cleaning solution, collecting the solution, and then filtering particles from the solution by using a membrane filter of 0.45- to 1.2-micron pore size. The collected particles on the filter are then counted and sized under a microscope of 45 to 100X magnification. This test then indicates surface cleanliness assuming that the majority of particles collected were removed by the flushing operation and represent the particulate contamination degree of the surface.

The total filterable solids test⁸ obtains particles in the same manner as the previous method, except instead of counting and sizing the particles under a microscope, the weight of the particles is obtained by using a sensitive weighing system. The wipe test⁷ is carried out by wiping clean filter paper across the surface of concern. The count and size of distribution of the particles lodged on the filter paper is again measured by microscopic examination. The vacuum cleaning test⁷ is conducted by vacuuming applicable portions, collecting the vacuumed particles on a 100-mesh screen and observing the screen with a 10-power magnifying glass. If any significant amount of particles are on the screen, the screen is flushed with an appropriate service fluid and the particles are filtered from the fluid by a membrane filter followed by microscopic examination for size and count.

Witness plates consisting of flat surfaces of various compositions and colors have been used in some applications. These plates are placed in strategic locations and are microscopically examined as indicators of particle fallout in the vicinity of sensitive surfaces. Aside from problems of accessibility, no assurance can be provided that these plates are truly representative of the surfaces of concern and are located in the proper areas. Nevertheless, if accessibility for removal of the plates is feasible as late as possible in the launch operation cycle, this method of ground contamination measurement has advantages over other methods since the sensitive spacecraft surfaces do not have to be contacted.

The previous methods provide indirect measurements of surface contamination. For the flushing and wiping methods, the particles from relatively large surfaces are concentrated on smaller collecting devices and thereby allow the examination of less area by high power microscopy. Although this allows the detection of particles less than 1 micron in size, the accuracy is questionable since it depends on the unknown particle removal or collection efficiency and reproducibility of the devices used. Also, with the exception of the witness plate method, the methods are usually impractical for use on assembled spacecraft in the field

since direct contact of the spacecraft or fluid is required. In most applications the spacecraft contractors would not allow such operations because of potential damage to the spacecraft or sensitive surfaces.

Direct Measurements. The only direct surface examination of assembled spacecraft presently performed is a visual inspection⁷ utilizing white or ultraviolet light. The visual inspection without magnification is relatively qualitative, dependent on the acuity of the inspector's vision. Under optimum conditions, the human eye can detect particles > 25 to 50 microns. It has been approximated that roughly 1000 particles > 50 microns on a surface, equivalent to MIL-STD-1246A Class 300, are required to allow a general impression of visible contamination since it is unlikely that the eye can focus on a few scattered particles in the visible size range. The ultraviolet light inspection would reveal only particles that fluoresce under ultraviolet radiation and is mainly used to detect surface films such as hydrocarbons.

A 10-power magnifying glass has been used to allow the detection of relatively small particles of high contrast (~5 microns); however, the time to count and size particles in this manner is considered excessive, no record is provided, and it is judged not suitable for field use.

New Developments in Measurement. Among new developments under investigation are a sonic velocity vacuum probe especially designed for the collection of particles down to 1 micron by Sandia Corporation⁹, quartz crystal microbalances (QCM) under development by Celesco Industries and various other corporations¹⁰, and a photometer developed by SAAB-Scandia of Sweden¹¹. These devices are subject to a considerable number of problems such as the vacuum probe that must have direct contact with the surface under consideration, which is not allowable on many spacecraft. The QCM will measure small changes in the mass of deposits on a crystal surface. However, they must be coated with an adhesive to bind particles to the surface. Otherwise, the microbalance will only measure the impulse of impacting particles. The recording and interpretation of such data is more complex than for adhesive coated microbalances. Also, the small size of a QCM requires that many be used to obtain statistically meaningful sampling areas. The SAAB photometer measures changes of specular reflectance due to particles, does not provide a measure of particle count or size, and requires the use of witness plates as opposed to direct measurements.

Because of this lack of suitable methods to measure the surface cleanliness of spacecraft in the field, an experimental program using photographic techniques was initiated.

APPROACH

Consideration was given to the use of photographic techniques

because it would allow a direct measurement of surface particulate contamination, provide a record of the degree of cleanliness, would not require physical contact with sensitive and vulnerable surfaces, and could potentially be performed in a short time period. All of these factors were judged of importance in obtaining field measurements.

Particle measurement using conventional photomicrographic techniques is a well established art^{12, 13}, but generally requires specimens that can be placed under a microscope. After precise adjustments, magnification up to 350X can be relatively easily photographed. For direct examination of spacecraft surface contamination it was believed impractical to utilize photomicrography for several reasons. The field of view decreases rapidly as the magnification power increases. Drinker and Hatch¹⁴ have indicated that a statistically meaningful sample requires the capture of at least 100 particles. Using this as a basis, the number of 35-mm photographs that would be required at various magnifications and cleanliness levels is shown in Table 1.

Table 1. Number photographs versus magnification power

<u>Item</u>				
<u>Lens Mag. Powers</u>	1X	4X	10X	40X
<u>Cleanliness Level</u>	<u>35-mm Photographs/100 Particles</u>			
MIL-STD-1246A				
Class 500	< 1	< 1	< 1	4
Class 300	< 1	< 1	3	37
Class 100	3	37	230	3,640
Class 50	23	364	2,300	36,400
Class 10	1,150	18,200	115,000	1,820,000
Field of View (sq mm)	870	55	8.7	0.55

It can be seen that at high magnification powers and low contamination levels extremely large numbers of photographs are required to capture 100 particles. From a practical standpoint the author assumed that approximately 37 photographs of 35-mm size are the upper limit of the number of photographs that can reasonably be analyzed within a practical time period. For this reason, based on Table 1, if contamination levels considerably below MIL-STD-1246A Class 300 (the visible contamination threshold) are to be measured, magnification powers exceeding approximately 6X would be impractical. This would theoretically allow measurements of cleanliness levels somewhat better than MIL-STD-1246A Class 100. This degree of magnification falls within the limits of macrophotography and led to its selection.

Other considerations leading to the elimination of photomicrography as a candidate were the field conditions under which the photographs are taken. These require a relative insensitivity

to small vibrations and thus a large depth of field is desirable. Because of irregular surfaces on the spacecraft, it is also desirable to have the viewing lens as far as possible from the surface under examination. Both conditions present difficulties at high magnifications since the depth of field and the working distance decreases with magnification power.

References 15 and 16 describe initial attempts to perform macrophotographic surface contamination studies on spacecraft STP 70-1 and 71-2 where particles in the 50- to 100-micron range were of concern. During these measurements it was noted that relatively little knowledge was available on the smallest size particle that could practically be measured on a spacecraft by macrophotographic means.

THEORY

Before embarking on experiments, an evaluation of some of the photographic parameters was conducted to determine the theoretical variables that might influence the particle measurement accuracy obtainable.

Diffraction Limit¹⁷

Photographic objective lenses have an ultimate physical limit in their ability to transmit an accurate image of point sources of light to the image plane. This is the diffraction limit of the objective. Although the reflection of light from particles is not a true representation of a point source of light, the diffraction limit of lenses enters into the consideration of variables that affect the image transmitted by the photographic objective.

Diffraction is a phenomenon which occurs whenever an aperture is placed in a light beam in such a way as to limit its diameter. In an optimally corrected photographic lens the spreading of the light caused by the aperture stop is manifested in the image plane by the appearance of the Airy disk, a circularly symmetric distribution of the light from a point source consisting of a bright spot with a system of rings of much weaker intensity around it. About 84 percent of the energy from the point is contained in the central disk. The diameter of the central disk is generally the only one considered and is defined by

$$d = 2.44\lambda F (1 + M) \quad (1)$$

where

- d = the central Airy disk diameter, microns
- λ = the light wavelength (~ 0.55 microns for visible light)
- F = the lens f number
- M = the magnification

The image produced by a photographic objective of point sources or objects such as particles approaching point sources is thus enlarged. The apparent size of a magnified point source in

the image plane is defined by

$$d_a = d/M \quad (2)$$

where d_a = the apparent diameter of a point source and M = magnification.

It can be expected that particles smaller than the apparent diameter produced by the Airy disk will thus appear at least as large as the apparent diameter and probably somewhat larger since they are not point sources, even if a perfect lens system is used. Table 2 shows the relationship between selected f numbers of a perfect lens and the apparent diameter of a point source for selected magnifications.

Table 2. Apparent diameter of point sources*

Objective f - number	Apparent diameter on image plane, microns				
	Magnification	1X	2X	4X	8X
1		2.7	2.0	1.68	1.5
1.4		3.8	2.8	2.3	2.1
2		5.4	4.0	3.4	3.0
2.8		7.5	5.6	4.7	4.2
4		10.7	8.0	6.7	6.0
5.6		13.7	11.2	9.4	8.5
8		21.5	16.0	13.4	12.0

*These data are for high contrast conditions

Although some cameras have minimum f numbers between 1 and 1.4, photographers generally use f numbers approximately three stops above the minimum f number to obtain good definition (resolution) with a reasonable small image of a point source (Airy disk). This is done because ordinary commercial grade lenses are not diffraction limited at small f numbers due to residual aberrations. By stopping the lens down with an internal diaphragm these aberrations are reduced and the lens more nearly approaches its diffraction limit.

With objectives specifically designed for macrophotography, it is possible to operate at the minimum f number with good resolution since lenses are manufactured to produce minimum aberrations even when the aperture is wide open. In general, such lenses have minimum f numbers between 2 and 4. A high quality macrophotographic lens was not available at The Aerospace Corporation and it was necessary to use a lens with a minimum f number of 3.5 which was not designed for macrophotography. For good resolution this lens was stopped to $f/8$. Per Table 2, the diffraction limit of such a lens would be 13.4 microns at the 4X magnification. This size can thus be predicted to be the diffraction limited size particle image seen through the lens, regardless of the actual size of the object.

Lens Contrast Modulation and Film Emulsion Spread

A photographic lens modulates the contrast between the object photographed and the background so that the image seen by the film has less and less contrast as the object becomes smaller¹⁸. The ability of the film emulsion to capture the image transmitted by the lens is related to the emulsion sensitivity¹⁹. The sensitivity of an emulsion to give good definition and to reproduce fine detail is limited by its microstructure at the exposure stage and after development. If an infinitesimally small point or narrow line image could fall on an emulsion layer, it would diffuse the light into a broadened point or line of an intensity that would diminish toward zero at the borders²⁰. The amount of spread is a function of the type of film used with greater spread for high speed than for lower speed films, such as microfilm as indicated in Figure 2.

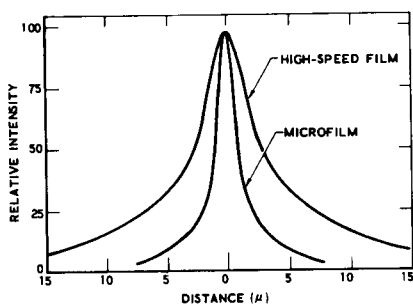


Fig. 2. Spread function of film

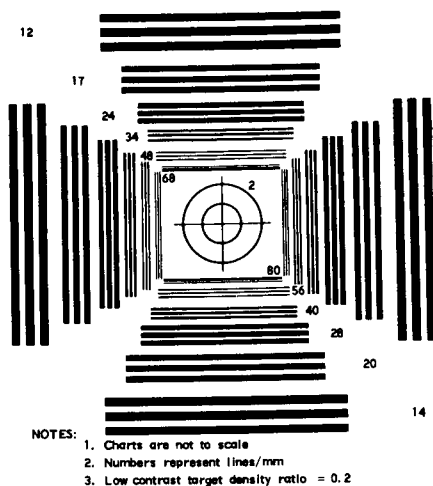


Fig. 3. High-contrast resolution test chart, density ratio = 1.4

This shows that slow, fine grain emulsions theoretically provide better and more accurate definition than high speed, coarse grain emulsions. For this reason two types of films were used for the experiment; a relatively fast Panatomic X film and a relatively slow High Contrast Copy film.

Lens/Film Resolution Thresholds

Subjects consisting of various contrast resolution targets are photographed using an identical lens with different types of film to determine resolution of the lens/film combination.

Figure 3 is a high contrast NBS target²¹ where contrast is a measure of the ratio of densities of the dark lines and the background. Density ratio is defined as follows¹⁹:

$$D = \log (I_{\max}/I_{\min}) \quad (3)$$

where D = density ratio, I_{\max} = the luminous intensity of the lines-candles, and I_{\min} = the luminous intensity of the background-candles.

The relative performance of the films used can be measured by determining the number of lines per mm that are distinguishable as separate and distinct lines on the negative (resolution).

Figure 4 shows the performance of two different speed films using such a test¹⁹. The curves labeled high and low contrast object represent the contrast modulation caused by the camera lens which decreases the object contrast in the image plane from its highest value when the lines are far apart to lower values as the line spacing decreases. The curves labeled high speed and high contrast film threshold represent the implicit threshold resolution values of the films which allow higher resolutions as the object contrast increases. The intersections of the film threshold curves with the lens contrast modulation curves are the resolution thresholds of the lens/film combinations as depicted on Figure 4. Note that the slower speed high contrast film has a considerably higher resolution threshold than the high speed film. While tests using bar type subjects are not representative of tests on point-type subjects, a similar resolution relationship exists for point subjects.

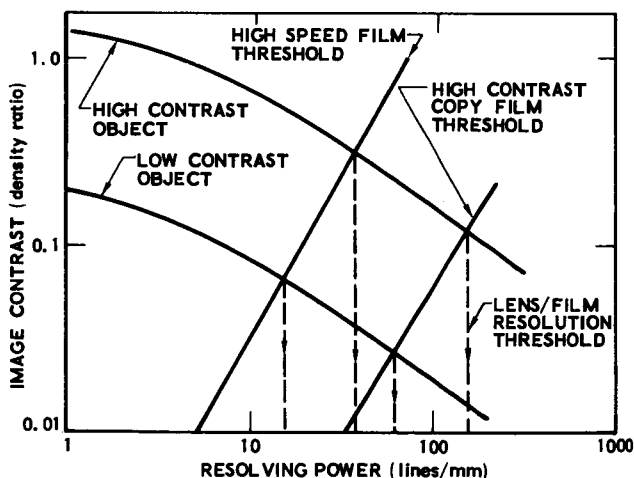


Fig. 4. Typical lens/film resolution thresholds

The diffusion of a point of light by both lens diffraction and emulsion spread is such that maximum intensity exists at the center and less intensity at the edges. As a result it can be expected that the contrast between the background at the image decreases at the edges so that the emulsion does not reproduce the complete size of the image. There is thus a compensating mechanism for diffraction and point spread enlargement which depends on emulsion sensitivity to contrast. It can be expected that as a photographic negative is processed to an enlarged print, further contrast reduction occurs and a given point image will appear smaller. Illustrations used in this report are enlarged prints of negatives. They are thus not necessarily true representations of the data. The negatives themselves were used to collect the actual data on particle count and size.

The illumination of the surface is an additional variable that must be considered. Decreasing intensity can be compensated for by increasing aperture opening or exposure times. The angle of illumination is important in the ability to distinguish between particles and surface roughness and also influences the sizing accuracy.

EXPERIMENTAL PROCEDURE

The basic experiment was designed to obtain 37X photomicrographs of certain areas of the artificially contaminated specimen for use as a baseline, followed by macrophotographs of the identical areas under varying magnifications and types of illuminations using a relatively high speed and slow speed film. The results would then be compared to determine the degree of contamination visible on the macrophotograph relative to the 37X photomicrograph baseline.

Prior to initiation of the primary experiment, the development of experimental specimens, particle sizing and counting techniques, plus photomicrographic and macrophotographic techniques was required. There was no attempt made to optimize on an absolute basis. The development of the technique was confined to the most practical usage of equipment available.

Specimen Preparation

The test specimen used for the experiment consisted of a 1/8-in. thick aluminum plate measuring 1 x 1 in., painted with white acrylic paint, and gridded with 2 x 2 mm grids as shown in Figure 5. The surface roughness was not measured. It is approximated that maximum irregularities in the paint projected 10 microns above the general surface.

The fly ash used to contaminate the specimen consisted of particles with a relatively wide size distribution, ranging from submicron to in excess of 100 microns. The substances contained within fly ash provide a wide range of colors from almost pure carbon black to white aluminum oxide, and almost colorless silica particles. This substance thus presented a good cross

section of potential surface contaminants with varying contrasts against a white background.

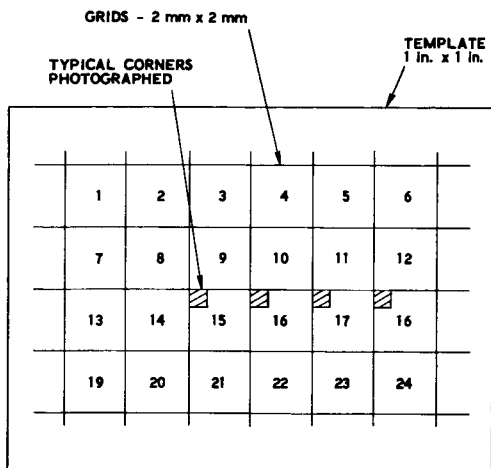


Fig. 5. Test specimen

The sample was artificially contaminated by mixing a relatively small amount of fly ash with solution consisting of 95 percent isopropyl alcohol and 5 percent by volume of liquid soap. The fly ash contained within the alcohol-soap solution was stirred and spread over the surface of the specimen until a relatively homogeneous amount of fly ash seemed to be covering the grids as observed by direct microscopic examination. After the alcohol evaporated, the fly ash remained on the surface to be used as the artificial contaminant. An initial attempt to utilize freon (MIL-C-81302A Type II) to suspend the fly ash was not successful since the fly ash did not stay in suspension long enough and coagulated quite rapidly. The alcohol-soap solution showed minimum coagulation of particles and good homogeneity of surface coverage by microscopic examination.

After the artificial contamination was accomplished, the sample was kept in a closed container to protect it from further contamination. It was only removed from the container when photographs were taken. Repeated examination indicated no apparent change in contamination as a result of these short exposure times.

Counting and Sizing Techniques

Photomicrographs. Photomicrography using 37X magnification was selected since it allowed the measurement of 1-micron particles with reasonable accuracy. The measurements were performed by projecting the negatives onto a white paper screen measuring 70 x 85 cm at a projection magnification of 30X for a

total magnification of 1110X. The projector was a Society for Visual Education Model 49 500-watt, 35-mm film strip projector and was equipped with a 5-in. focal length, f/3.5 coated lens. At the 1110X magnification a 1-micron particle would measure slightly above 1 mm and was easily visible. The outlines of the particles on the screen were traced, the paper screen removed, and the traced particle sizes measured using a metric ruler graduated in millimeters. It is estimated that the accuracy of measurement using this method was $\pm 1/2$ mm, equivalent to approximately $\pm 1/2$ micron at the 1100X total magnification. The number of particles was determined by simply counting the particles traced. A tabulation of size and count was then made by totaling the number of particles within specific size ranges.

Macrophotographs. For the 1X, 2X, 4X and 6X macrophotographs similar sizing, counting and tabulation techniques were used. Table 3 shows the sizing accuracies estimated for the various macrophotographic magnification powers used.

Table 3. Sizing accuracies

<u>Photo Magnification</u>	<u>Screen Magnification at 30X Projection</u>	<u>Sizing Accuracy, Microns</u>
6X	180X	± 3
4X	120X	± 4
2X	60X	± 8
1X	30X	± 16

Photomicrographic Technique Development

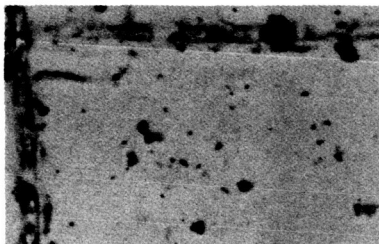
The test specimen was placed under a Leitz Ortholux microscope with a 35-mm Leica camera attachment, and 35-mm photomicrographs at 37X magnification, using Kodak Panatomic X film, were taken of the upper left hand corner of each of the 24 grids. The field of view covered by each photograph was approximately 0.6 sq mm. The initial photographs were taken with conventional microscopic illumination using a light in an almost vertical angle position. Upon completion of this phase, the illumination angle was changed to ~ 30 -deg angle from the horizontal and photomicrographs were taken with this oblique illumination. Standard methods were used to develop the Panatomic X film.

It was found that the obliquely lighted photomicrographs allowed distinguishment between particles and shadows and also indicated the roughness of the white painted background. Figure 6 shows an example of a vertically and obliquely lighted 37X photomicrograph of grid no. 4 on Figure 5.

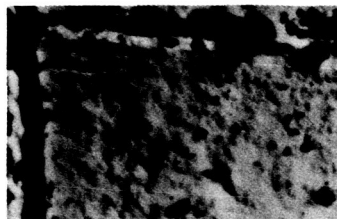
By comparing the vertically and obliquely lighted photomicrographs, it was concluded that a large number of the spots appearing on the vertically lighted photomicrographs were not particles but were reflections created by the roughness of the background. As an example, on grid no. 4 the vertical lighting

led to a count of 72 spots, whereas the oblique lighting only revealed 34 true particles. It thus appeared that vertically lighted photomicrographs of rough surfaces were not suitable for analysis and that oblique lighting would be required.

Vertical lighting



Single oblique lighting



37X photo, 1.6X print, and 60X total enlargements

Fig. 6. Vertical vs. oblique lighting 37X photomicrographs

Macrophotographic Technique Development

Equipment. The macrophotographic equipment consisted of a Leica M2 camera fitted with a 135-mm $f/4.5$ Hektor lens for 1X magnifications and a 50-mm, $f/3.5$ Elmar lens for 2X, 4X and 6X magnifications. These were the best lenses available to the author at The Aerospace Corporation and procurement of more optimum equipment was not within the scope of this study. It is reasonable to postulate that some modern macro lenses could have been more effective.

The camera was equipped with a Visoflex II reflex housing and extension bellows were inserted between the lens and camera body for reproduction scales up to 4X. For 6X magnifications extension tubes were inserted between the lens and camera body since the available bellows could not extend far enough. Illumination was produced by Colortran Multi-6, 650-watt quartz lights and photographs were taken at a variety of angles. It was decided to use three illumination angles for the macrophotographs; approximately perpendicular to the surface, single oblique at approximately 30 deg to the surface, and two diametrically opposite oblique lights at 30 deg to the surface. Figure 7 shows the vertically lighted photographic set-up used for the macrophotograph at 1X magnification.

Quartz lamps were used since field conditions required explosion-proof equipment. All pictures were taken at $f/8$ and the exposure time was varied in accordance with the degree of magnification.

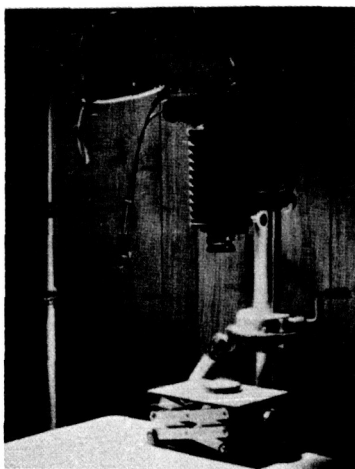


Fig. 7. Vertically lighted photographic set-up

Illumination, Exposure and Projection. Experiments were conducted on illumination and exposure techniques. Also, the variation in particle visibility with magnification power was tested to determine the most practical magnification with the available equipment. Photographs at 1X, 2X, 4X and 6X magnifications of the identical specimen areas were taken using illumination at oblique and vertical angles. Optimum exposure for each picture was obtained by using three different exposure times at a constant f/8 aperture. The technique provided approximately equal density negatives. It was concluded that at magnifications up to 6X vertical lighting would be best for close-up photographs since it allowed more accurate sizing.

The particle visibility at various photographic and projection magnification powers was tested by analyzing identical portions of the template using photographs taken at various magnifications and projecting each at 60X, 30X and 15X magnifications. The 30X projection magnification was selected as the best compromise. Table 4 shows the results in condensed form for 30X projection magnification.

Table 4. Macrophotographic particle distributions

Size, Microns	No. of Particles at Photographic Magnification Powers			
	6X	4X	2X	1X
≥ 2	--	--	--	--
≥ 10	--	--	--	--
≥ 12	65	--	--	--
≥ 16	62	61	--	--
≥ 20	51	54	--	--
≥ 25	38	29	30	12
≥ 32	21	23	25	9
≥ 46	12	13	15	9

It can be noted that relatively small differences exist between the 6X and 4X size and count distributions, but that at photographic magnifications below 4X major changes in particle visibility occur. For this reason 4X was selected as the most practical macrophotographic magnification power.

PRIMARY EXPERIMENT

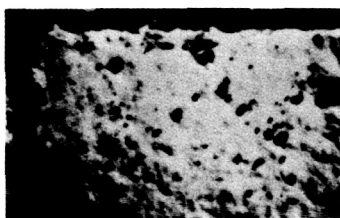
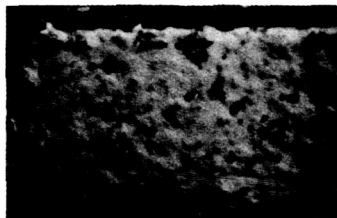
The basic experiment, using the techniques developed, was performed by comparing 4X macrophotographs with 37X photomicrographs of identical areas on the test specimen, using Panatomic X and High Contrast Copy film.

37X Photomicrographs

In order to limit the number of photographs required to obtain statistically meaningful data, the artificially contaminated sample was examined under a microscope and it was estimated that four 37X photomicrographs would capture approximately 200 particles. Figure 8 shows an example of a 37X photomicrograph using Panatomic X film and also shows the same area for High Contrast Copy film. The results of particle size and count analysis derived from 37X photomicrographs are shown in Table 5 for the two types of film used.

Panatomic X film

High contrast copy film



37X photo, 1.6X print, and 60X total enlargements

Fig. 8. 37X photomicrographs, grid no. 17

It can be noted that the High Contrast Copy film provided considerably better visibility at particle sizes less than 12 microns.

4X Macrophotographs

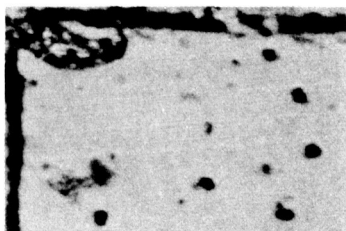
The fly ash contaminated template was photographed at 4X magnification using vertical illumination with both Panatomic X film and High Contrast Copy film and the same areas previously photomicrographed at 37X were examined and compared for particle count and size.

Table 5. 37X photomicrographic particle distributions

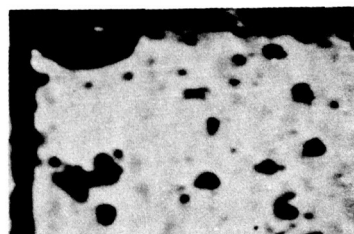
Size, microns	Film	
	Panatomic X	High Contrast Copy
	Number of Particles/1.5 sq mm \geq Stated Size	
≥ 2	170	234
≥ 6	168	207
≥ 12	114	117
≥ 20	55	58
≥ 32	20	18
≥ 46	5	5
≥ 64	4	3
≥ 90	2	1

As an example, Figure 9 shows the upper left hand corner of grid no. 15 photographed with Panatomic X film and High Contrast Copy film. These pictures are enlarged to a total of 60X for purposes of illustration only. The actual enlargements for sizing and counting were 120X.

Panatomic X film



High contrast copy film



4X photo, 15X print, and 60X total enlargements

Fig. 9. 4X macrophotographs, grid no. 15

The results of the macrophotographic count and size distribution as compared to the High Contrast photomicrograph count and size previously described are provided in Table 6.

It can be noted that the smallest particle size visible on the macrophotographs was 16 microns for both films. The total number of particles visible on the macrophotographs was 25 and 31 percent, respectively, for the Panatomic X and High Contrast Copy films as compared to those visible on the photomicrographs. It can also be noted that relatively poor particle count correlation exists at sizes 16 microns and above between the macrophotographs and the photomicrographs.

Table 6. Macrophotographic vs. photomicrographic particle distribution

<u>Film</u>	Panatomic X		High Contrast Copy
<u>Magnification</u>	4X	4X	37X
<u>Size, microns</u>	<u>No. of Particles/1.5 sq mm \geq Stated Size</u>		
≥ 2	--	--	234
≥ 4	--	--	232
≥ 6	--	--	207
≥ 12	--	--	117
≥ 16	58	73	81
≥ 20	55	71	58
≥ 32	39	37	18
≥ 46	7	11	5
≥ 64	3	6	3
≥ 90	1	3	1

DISCUSSION

An explanation for the lack of correlation was sought by comparing the sizes measured on the macrophotographs with the size of identical particles measured on the photomicrographs. This was done by measuring the position of the particles relative to the template grid lines using a rectangular coordinate system. Each particle was then numbered and a particle by particle comparison of size was made on the four grid portions examined. The results are shown on Figure 10 for Panatomic X film and on Figure 11 for High Contrast film by plotting the sizes of particles obtained from macrophotographs against the size of the identical particle from photomicrographs. Note that for both films most of the macrophotographic sized particles appear larger than the photomicrographed particles since a majority of points are above the equal size 45-deg lines drawn on both figures. The reason for the point spread can most likely be explained by photographic considerations discussed in the section on theory, such as lens diffraction, emulsion spread, contrast modulation, etc. The constant f/8 number used for the macrophotography produces a diffraction limited size of approximately 13.4 microns as shown in Table 2. When coupled with the point spread induced by the film, it is not unreasonable to expect a minimum apparent size of 16 microns, although the actual size of a few particles captured by the macrophotographs was as small as 6 microns. It is assumed that these were especially high contrast particles. The apparent smaller than actual size particles (below the equal size line) is probably due to the low contrast of certain particles and the contrast modulation of the lens which would reduce the size of the image as compared to the subject.

Figure 12 shows the cumulative particle count and size distributions, with curves A and B representing the particle count and size distribution for photomicrographs, using High Contrast

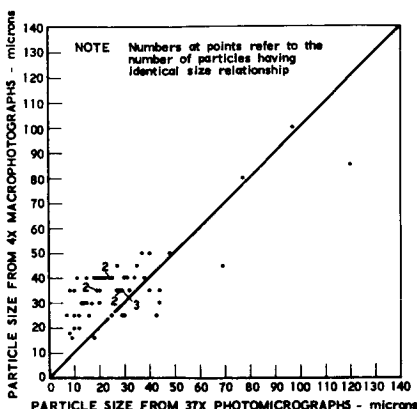


Fig. 10. Particle Size, Panatomic X film

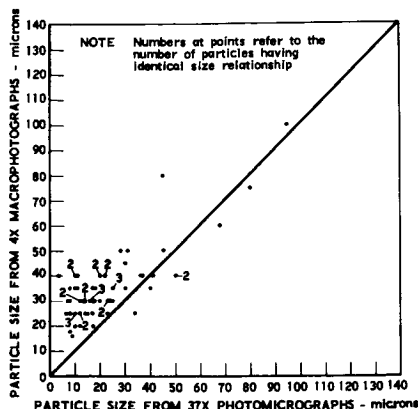


Fig. 11. Particle Size, High Contrast Copy film

Copy film and Panatomic X film, respectively. Curves C and D represent the particles captured and counted on macrophotographs, but located and sized on the photomicrographs. Curves E and F represent the particles captured, counted and sized on macrophotographs.

It can be seen that curves C and D merge with curves A and B at approximately 32 microns. This indicates that good correlation of count and size would have been obtained at this size if the true particle size had been measurable on the macrophotographs.

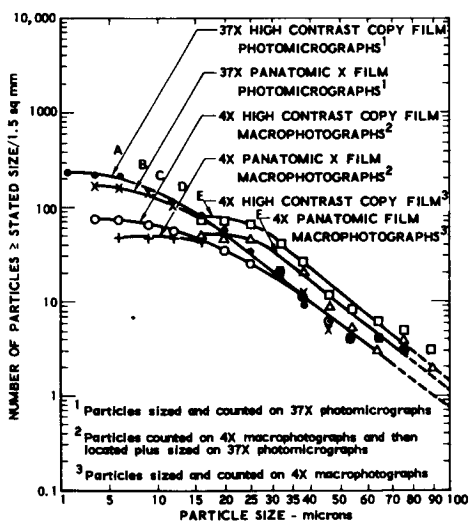


Fig. 12. Cumulative Experimental Results

A comparison of curves E and F with curves A and B showed that the apparent particle count at a given size on the macrophotographs started to exceed the count on the photomicrographs at 20 microns for Panatomic X film and 16 microns for High Contrast Copy film. The macrophotographs thus indicated a higher than actual contamination degree at sizes above these values.

Although the accuracy and particle visibility obtained with macrophotography was not as high as desired, the experiment indicated that this method is usable for field surface contamination measurements where a degree of measurement above the "no visible" surface contamination is desired. Also, it provides direct measurements, requires no contact with surfaces and provides a permanent record. It should be noted that the cleanliness of the environment surrounding the surfaces must be closely controlled after photographic accessibility is no longer feasible to assure that the measured cleanliness is retained.

Conclusions

Based on the experiments conducted and the equipment used, it is concluded that field contamination measurement by 35-mm, 4X macrophotography provides conservative results within reasonable limits for sizing and counting particles ≥ 16 microns. It is also concluded that adoption of the technique described by these experiments can realize the inherent advantages of photographic measurement of (1) no direct contact between the measuring equipment and the surface undergoing measurement is necessary, (2) a direct measurement is obtained, and (3) a permanent record is provided. The experiments provided sufficiently encouraging results to warrant further exploration with more optimized equipment.

Recommendations

For the technique described, it is recommended that 560-watt quartz light illumination perpendicular to the surface be used and that a slow speed film such as High Contrast Copy film be employed with a minimum of 5 exposures per measurement. For sizing and counting particles from the macrophotographic negatives obtained, a 30X projection is recommended.

Future work by other investigators should consider the feasibility of using more modern optical equipment and techniques which are more specifically related to macrophotographic procedures in order to enhance the results that may be obtainable. A partial listing of potential refinements is provided.

Optics. In place of the infinity corrected Triplet Elmar lens, use lenses specifically designed for macro-optics such as a 55-mm f/2 Ultra-Micro Nikkor lens used in reverse position.

Photographic System. Match the types of surfaces to be examined, field conditions, lens, film, filtering, illumination, and film processing for optimum results.

Particle Measurement. Consider the adaptation of automatic image analysis techniques to measure particle quantities and sizes in place of the laborious manual techniques used. Such techniques could probably reduce the time for analysis by an order of magnitude.

Advanced Techniques. Consider the use of stereo photography and color film as means of enhancing performance.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the valuable contributions made by the following: Mr. Craig Smith who supervised some of the tests and participated in the analysis; Mr. Theodore Carrington who performed the photography; and Mr. James Richardson who acted as advisor on photomicrography.

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